

# ON THE ANALYSIS AND DIGITIZATION OF MONGOLIAN ARTIFACTS

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## ABSTRACT

Mongolian artifacts (clothing, architecture, furniture, carpets, and tools) exhibit distinctive patterns rooted in nomadic traditions. This article presents a method to analyze and digitize those patterns. The method comprises four serial modules: representation, analysis, virtual modeling, and physical modeling. The representation module prepares artifact data for analysis. The analysis module detects basic motifs associated with the artifact's patterns using a predefined taxonomy of motifs: geometric, plant, symbol, animal, and nature based. Each motif identified through this classification is then expressed in mathematical form. The virtual modeling module aggregates the mathematically defined motifs underlying the artifact into a single compound motif and converts it to a CAD model using a point-cloud-to-CAD-model approach. The physical modeling module generates manufacturing data from the CAD model. In this study, STL data (triangular tessellation of the CAD model) serve as the manufacturing input for 3D printing. A case study validates the method by successfully recreating an embroidered pattern consisting of several geometric motifs found in a Mongolian artifact. Beyond preservation, the method can support museum display, education, and souvenirs. It can also promote standardized documentation across curators, designers, and researchers. As the number of skilled artisans declines, this digital design and manufacturing pipeline provides a practical, sustainable means to document, replicate, and disseminate Mongolian cultural heritage, thereby safeguarding tradition and identity.

*Keywords: Heritage, Mongolian Culture, Geometric Modeling, CAD, Digitization*

## 1 INTRODUCTION

Human civilization exhibits a rich and diverse cultural heritage developed over time. Many ethnic groups have contributed to this shared heritage, adding unique ideas and elements. To express their cultural identity and aesthetic sensibility, different ethnic groups around the world incorporate distinctive motifs into their prayer places, housing, clothing, utensils, and other artifacts. Hann [1] examines how geometry, symmetry, and repetition underpin artistic expression across world cultures. Drawing on examples from Islamic, Celtic, East Asian, African, classical, and modern traditions, Hann explores how structural design conveys symbolic meaning and reflects cultural identity and unlooked links between visual order with philosophical and spiritual ideas, showing that patterns are not merely decorative but express systems of belief and perception. By integrating design theory, anthropology, and semiotics, Hann demonstrates that symmetry functions as a universal language connecting mathematics, aesthetics, and cultural communication. In order to understand this design and cultural interplay more comprehensively, consider the case of the Ainu people. The Ainu are an indigenous group native to northern Japan, mainly Hokkaido, and parts of the Russian Far East including Sakhalin and the Kuril Islands. They have East Asian ancestry that is distinct from the majority Japanese population and have developed a unique artistic tradition. Nishikiya [2] identifies five key motifs in Ainu design: Atushi, Aiushi, Shik-noka, Uren Moreu, and Moreu. The Atushi, which comes from bark-fiber garments, represents the earliest stage of pattern making. The Aiushi is the basic embroidered motif that forms the foundation of Ainu decorative art. The Shik-noka consists of continuous linked forms that resemble temple bells or flowers. The Uren Moreu developed from these as knotted or twisted variations. The Moreu, a spiral motif, became the mature form that symbolizes movement and protection. Together, these motifs show how Ainu ornamentation evolved from simple textile patterns into refined symbolic art. Let us consider, which is our focus, Mongolian culture, as well. Since ancient times, the Mongolian nomadic lifestyle has shaped a portable craft tradition in which functional items like chests, garments,

saddles, and ger components are decorated with symbolic geometric motifs reflecting aesthetic refinement, spiritual meaning, and harmony with nature. For example, the online database in Ref. [3] provides a comprehensive collection of motifs found in Mongolian, Chinese, India, Iranian, Turkish, Buryatian, and Tuvan cultures. It provides illustrations, sources, and the significances of the motifs. Chinggis Khaan National Museum [4] also provides an illustrative online database of Mongolian artifacts that represents the rich heritage of Mongolia from ancient time to now. Some authors have studied the characteristics of Mongolian motifs found in contemporary paintings. For example, Ikkert [5] proposes a comprehensive methodological framework for interpreting the paintings of the Mongolian artist B. Sharav. The study combines the identification of cultural constants with iconological analysis to uncover the deeper semantic layers of Sharav's works. It emphasizes that the Mongolian ornament functions as a key cultural constant and serves as an initial iconological image, helping to reveal the compositional unity and symbolic depth of *Mongol Zurag* multi-figure and multi-plot paintings. However, since the objective of this study is to digitize Mongolian motifs, finding out the basic motifs, as other authors did for the Ainu motifs [6] is the path that will be considered in this article.

Accordingly, the rest of this article is organized as follows. Section 2 presents a method for analyzing and digitizing Mongolian patterns consisting of some predefined motifs. Section 3 presents a case study showing the efficacy of the geometric modeling and digitizing method. Section 4 provides the concluding remarks.

## 2 METHOD

This section outlines the proposed method for the geometric modeling and digitization of Mongolian motifs. Prior to introducing the method, a review of selected studies related to the modeling and digitization of cultural artifacts is presented, with particular attention directed toward research focusing on motif-based modeling and digital reconstruction.

Rojas-Sola et al. [7] presented a feature-based reconstruction of Agustín de Betancourt's double-acting steam engine using historical 2D engineering drawings and archival documents. Through visual inspection and detailed analysis of past records, they identified and modeled key components such as pistons, beams, and valves using an off-the-shelf CAD software package. The resulting 3D reconstruction accurately reproduced the engine's kinematic operation and demonstrated the mechanical symmetry and design principles of Betancourt's original work. A similar approach has also been adopted by other researchers [8–10]. Barbieri et al. [11] used digital photogrammetry to capture the 3D geometry of a sandstone Ionic capital exhibited at the Brettii and Enotri Museum in Cosenza, Italy. A dense point cloud of approximately 10 million points with a spatial resolution of about 0.3 mm was reconstructed using Agisoft Metashape Pro, followed by mesh repair and surface modeling in Blender and reverse-engineering software to produce a CAD-compatible model. Topology optimization was then applied to determine the optimal material distribution within the support structure, creating a lightweight yet mechanically efficient design manufactured through additive techniques. This digitally optimized support ensured even load distribution, minimized stress concentration, and enhanced the structural stability, conservation, and aesthetic presentation of the artifact. Chen and Cai [12] developed a CAD-integrated design framework for Guangxi cultural creative products using multi-modal data analysis. They extracted cultural features, including patterns (flowers, birds, mountains), color schemes, and semantic attributes, through the convolutional neural networks (CNNs) for image data and recurrent neural networks (RNNs) for text data. These extracted features were optimized using particle swarm optimization (PSO) and transfer learning algorithms to align traditional aesthetics with modern market needs. This approach helped solve real-life challenges of low design efficiency and limited innovation in Guangxi embroidery-based products by enabling data-driven feature extraction and design automation, reducing design time while preserving cultural identity. The main challenges included the distribution mismatch between cultural and market data and the need for human designers to interpret cultural nuances. Goel et al. [13] recreated traditional Indian jewelry using computer-aided geometric modeling. They defined eight traditional motifs, namely Heart, TikhaPyala, TikhiChoki, GoleChofuliya, TedaChand, KhanchKoyali, Ful, and ChidiPatti, by parametric equations based on geometric primitives such as lines, circles, and arcs. The motifs were combined into ornamental patterns using an off-the-self CAD software's application programming interface (API). The method requires manual aesthetic adjustment ornamental designs. Tashi, Ullah, and collaborators [14–16] developed an analytical point-cloud-based geometric modeling method to reconstruct traditional Ainu motifs, representing each motif through polar coordinate parameters of angle and distance. This approach enables accurate modeling

without explicit algebraic equations and was applied to all fourteen basic Ainu motifs. The resulting analytical point clouds can be combined and converted into CAD models for virtual and physical prototyping. The notion of analytical point cloud has been proven to be effective in reconstructing engineering artifacts (unique product (mug), gears, turbine blades and so on) from limited and incomplete information, e.g., see [17–19]. In this article, for the sake of modeling the concept of analytical point cloud is used because of its scalability and modeling capacity.

Accordingly, the proposed method for analyzing and replicating Mongolian artifact patterns consists of four sequential modules: representation, analysis, virtual modeling, and physical modeling. The overall workflow is illustrated in Figure 1.

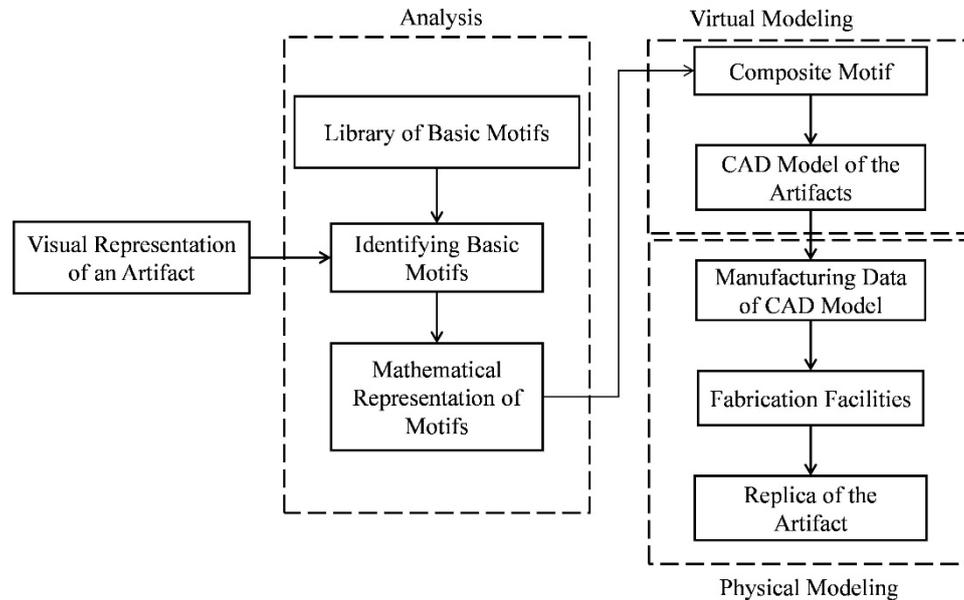


Figure 1. Schematic representation of the proposed method, showing the sequential modules of representation, analysis, virtual modeling, and physical modeling

The process begins with a visual representation of the artifact, which serves as the foundation for further analysis by providing a structured description of the surface geometry and decorative features. From this representation, the method identifies basic motifs embedded in the patterns. Identification is guided by a library of predefined motifs, which includes geometric, plant, symbol, animal, and nature-based categories. Each motif identified in the artifact is then expressed in mathematical form, ensuring consistency, precision, and comparability across different artifacts.

The mathematically defined motifs are aggregated into a composite motif that represents the overall decorative design of the artifact. This composite motif is subsequently transformed into a CAD model using a point-cloud-to-CAD-model approach. The CAD model functions as a digital replica of the artifact, capturing both the motif composition and structural details.

Finally, the CAD model is converted into manufacturing data. In this study, triangular tessellation was employed to generate STL files, which are suitable for additive manufacturing. These data are then transferred to fabrication facilities, such as 3D printers, to produce a physical replica of the artifact. This stage ensures that the digital models can be materialized, allowing both preservation and tangible reproduction of cultural motifs.

However, the taxonomy of Mongolian motifs is critical to the proposed method described above. This taxonomy is shown in Table 1, which is based on the database corresponding to Ref. [3]. As shown in Table 1, Mongolian traditional art employs a diverse set of motifs categorized into five groups: geometric, plant, symbol, animal, and nature. Each category embodies cultural, spiritual, and practical meanings deeply rooted in nomadic traditions.

Geometric motifs include five distinct shapes: square, circle, spiral, T-shape, and Ulzii. The square (G-1) symbolizes the number four and embodies ideas of balance, order, and cosmic perfection, representing earthly strength and solidity. The circle (G-2) is associated with the sun, symbolizing warmth, vitality, and the life-giving energy central to agricultural cycles. The spiral (G-3) carries dual meanings of life and death depending on its direction, while also representing infinity, continuity, and

cosmic rhythms. The T-shape (G-4), widely recognized as the “alkhan” pattern, references traditional tools such as ropes for tying foals and hammers, and symbolizes strength and continuity. It is prominent in both traditional and modern Mongolian design, including textiles, furniture, and interiors. The Ulzii pattern (G-5), also known as the Eternal Knot, represents harmony, interconnectedness, and the cyclical nature of life, often linked to fortune, longevity, and universal unity.

Table 1. A taxonomy of Mongolian motifs

No	Geometry (G)	Plant (P)	Symbol (S)	Animal (A)	Nature (N)
1	 Square	 Bud	 Coin type	 Hornlike	 Cloud
2	 Circle	 Trifurcate	 Flame	 Horse	 Tree
3	 Spiral	 Palmetto	 Hudack	 Butterfly	 Tendrill curl
4	 T-shape	 Leaf	 Chintamani	 Cow-nose	 Wave
5	 Ulzii	 Multipedal flower	 Heart	 Bird	 Mountain shape

Plant motifs capture themes of growth, renewal, and harmony with nature. The bud (P-1) symbolizes potential and new beginnings, while the trifurcate design (P-2) expresses branching growth and balance, often associated with the triadic concepts of life. The palmetto (P-3) depicts fan-shaped palm leaves and is widely used in ornamental arts. The leaf motif (P-4) conveys prosperity, fertility, and seasonal renewal. Floral motifs (P-5), particularly four-, six-, and eight-petal patterns, reflect Mongolia’s rich biodiversity and appear frequently in embroidery and textile arts.

Symbol motifs often appear in rituals and state ceremonies. The coin motif (S-1) represents wealth, prosperity, and spiritual abundance. The flame (S-2) conveys ascent and purification, expressing the hope that good flourishes while evil is consumed. The Hadaq motif (S-3), appearing in five colors, symbolizes kindness, purity, and the eternal sky, with each color linked to ceremonial contexts. The Chintamani (S-4) represents the precious wish-fulfilling gem, symbolizing wisdom and purity. The heart motif (S-5), though less traditional, has been integrated in modern contexts to express universal values of love and compassion.

Animal motifs emphasize the cultural and spiritual importance of fauna. The horn motif (A-1) and the horse motif (A-2) represent strength and the qualities of the Precious Horse, symbolizing intelligence and gentleness. The butterfly (A-3) conveys wishes for beauty and wisdom, while the cow-nose motif (A-4) reflects prosperity and the bond between nomads and livestock. The bird motif (A-5) symbolizes freedom and independence, resonating with Mongolia’s vast open landscapes.

Nature motifs embody elements of the environment. The cloud (N-1) signifies rain and renewal, while the tree motif (N-2) represents life, growth, and vitality. Tendril curls (N-3) serve as connecting elements, symbolizing unity and interdependence. The wave motif (N-4) captures movement and rhythm, often incorporated into carpets and woven goods. The mountain motif (N-5) symbolizes stability, strength, and the spiritual essence of Mongolia’s natural landscape.

### 3 RESULTS

This section presents a case study in which the pattern located at the center of the artifact (highlighted by the black square in left-hand side picture in Fig. 2) is examined. The objective is to generate the CAD data corresponding to this pattern. The pattern comprises both geometric and symbolic motifs. Specifically, the following motifs are identified: the geometric motif denoted as G-2 (circle), the symbolic motif denoted as S-1 (coin), a partial instance of S-1, and the geometric motif denoted as G-3 (spiral). In addition, several circular arcs (i.e., a modified motif of G-2), which are not indicated in the right-hand image of Fig. 2, are required to fully define the pattern. To model these motifs, four geometric entities are employed: the circle, circular arc, astroid, and logarithmic spiral. The mathematical representations of these entities are shown by the following equations. The geometric entities used to construct the motifs are expressed in parametric form with respect to a local reference point  $(x_c, y_c)$ , which serves as the center or anchor of each entity.

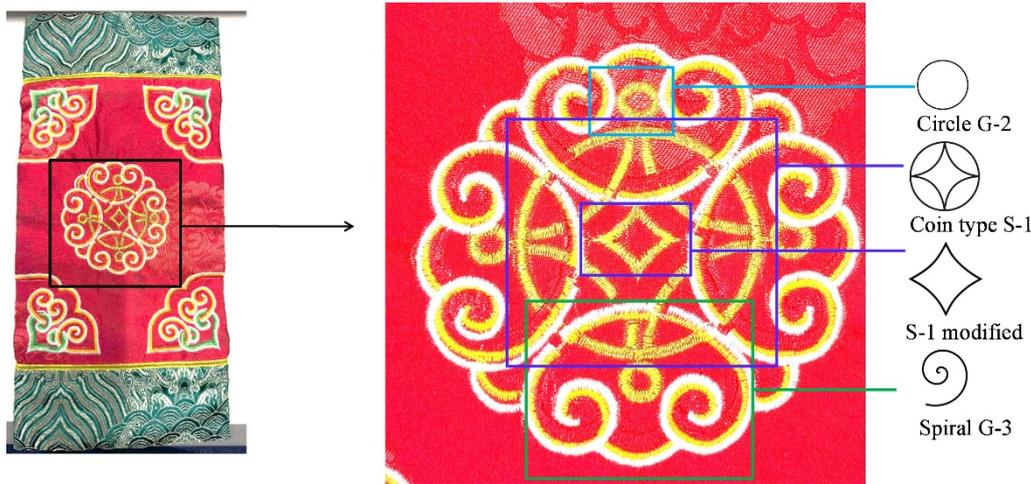


Figure 2. A Mongolian artifact exhibiting geometric motifs

A point  $(x, y)$  on the circumference of a circle is defined as follows:

$$x = x_c + a \cos \theta, \quad y = y_c + a \sin \theta, \quad 0 \leq \theta < 2\pi \quad (1)$$

In equation (1),  $\theta$  is in the angle in radians in the anti-clockwise direction from  $x$ -axis,  $a$  is the radius of the circle. A point  $(x, y)$  on the circular arc is defined as follows:

$$x = x_c + a \cos \theta, \quad y = y_c + a \sin \theta, \quad \theta_1 \leq \theta \leq \theta_2 \quad (2)$$

In equation (2),  $\theta_1$  and  $\theta_2$  are the bounding angles of the circular arc that are measured in the anti-clockwise direction from the  $x$ -axis and  $a$  is the radius. The astroid is defined as follows:

$$x = x_c + a \cos^3 \theta, \quad y = y_c + a \sin^3 \theta, \quad 0 \leq \theta \leq 2\pi \quad (3)$$

In equation in (3),  $\theta$  is in the angle in radians in the anti-clockwise direction from  $x$ -axis,  $a$  is the characteristic length (distance from center to cusp). The logarithmic spiral is defined as follows:

$$x = x_c + ae^{b\theta} \cos \theta, \quad y = y_c + ae^{b\theta} \sin \theta, \quad \theta_{min} \leq \theta \leq \theta_{max} \quad (4)$$

In equation (4),  $a$  is the initial radius (scaling factor) that determines spiral's starting size and  $b$  is the growth-rate parameter that controls how tightly or loosely the spiral expands. If  $b > 0$ , then spiral expands outward (radius increases as  $\theta$  increases). If  $b < 0$ , the spiral contracts inward (radius decreases as  $\theta$  increases). Figure 3 shows the examples of the above-mentioned entities. As seen in Figure 3, the circle is centered at the origin  $(x_c = 0, y_c = 0)$  with radius  $a = 20$ . The arc is centered at  $(x_c = -30, y_c = 10)$  spanning  $90^\circ$  from  $\theta_1 = \pi/4$  ( $= 45^\circ$ ) to  $\theta_2 = 3\pi/4$  ( $= 135^\circ$ ). The astroid is centered at  $(x_c = 30, y_c = -30)$  with  $a = 15$  as its characteristic length. The logarithmic spiral is anchored at  $(x_c = -30, y_c = -30)$  with scaling factor  $a = 5$  and growth-rate parameter  $b = 0.15$  (expanding outward) where  $\theta_{min} = 0$  ( $0^\circ$ ) and  $\theta_{max} = 3\pi$  ( $540^\circ$ ).

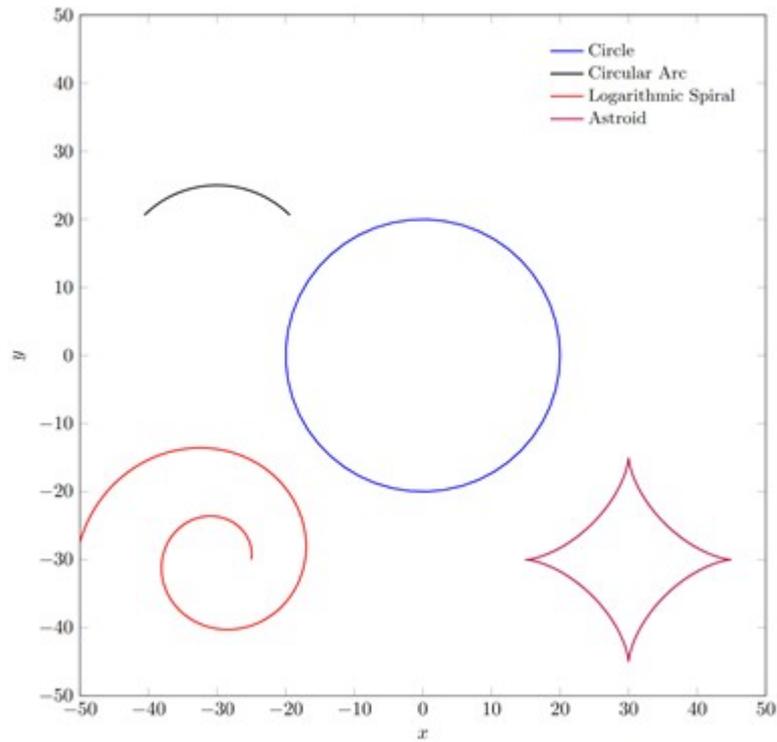


Figure 3. The geometric entities used in this study.

However, for the sake of modeling, a point on any of the geometric entities  $(x,y)$  may need to be translated, rotate, reflect, and scaled. The mathematical settings of these transformation are as follows:

$$x_t = x_r + s_x(\varepsilon_x(x - q) + (1 - \varepsilon_x)q - x_r) \cos \varphi - s_y(\varepsilon_y(y - p) + (1 - \varepsilon_y)p - y_r) \sin \varphi + \Delta x \quad (5)$$

$$y_t = y_r + s_x(\varepsilon_x(x - q) + (1 - \varepsilon_x)q - x_r) \sin \varphi + s_y(\varepsilon_y(y - p) + (1 - \varepsilon_y)p - y_r) \cos \varphi + \Delta y \quad (6)$$

In equations (5)-(6), the ordered pair  $(x,y)$  denotes the original point coordinates and the ordered pair  $(x_t,y_t)$  represents the transformed coordinates. The ordered pair  $(x_r,y_r)$  specifies the center of rotation and scaling. The parameter  $s_x$  and  $s_y$  are the scaling factors along the  $x$ - and  $y$ -axes, respectively. The parameter  $\varphi$  represents the rotation angle measured in radians, where positive values indicate counterclockwise rotation. The coefficients  $\varepsilon_x$  and  $\varepsilon_y$  are reflection parameters, taking values of +1 when reflection is inactive and -1 when reflection about the specified line is applied. The parameters  $q$  and  $p$  define the reflection lines  $x = q$  and  $y = p$ , respectively. Finally,  $\Delta x$  and  $\Delta y$  denote the translation distances along the  $x$ - and  $y$ -axes, respectively. The settings of the parameters for performing, translation, rotation, scaling, or reflection are summarized in Table 2.

Table 2. Settings of the transformation parameters.

Parameters	Translation	Rotation	Scaling	Reflection ( $x = q$ )	Reflection ( $y = p$ )
$s_x$	1	1	variable	1	1
$s_y$	1	1	variable	1	1
$\varphi$	0	variable	0	0	0
$\varepsilon_x$	+1	+1	+1	-1	+1
$\varepsilon_y$	+1	+1	+1	+1	-1
$q$	-	-	-	variable	-
$p$	-	-	-	-	variable
$(x_r,y_r)$	-	variable	variable	-	-
$\Delta x, \Delta y$	variable	0	0	0	0

The transformation settings were applied to construct a composite pattern for CAD modeling. The composite pattern consists of two circles (small and large), three types of circular arcs, two types of astroids (small and large), and a logarithmic spiral. The transformation process is illustrated in Figure 4.

First, a logarithmic spiral was generated and reflected about a vertical line to form its symmetric counterpart. A circular arc was then added to connect the two spirals. A small circle was placed between the inner ends of the spirals, followed by another circular arc linking them above the small circle. The entire structure was rotated three times to create four symmetric sectors. Between the sectors four circular arc were added to further connect the sectors. Finally, a large circle and two astroids (small and large) were positioned concentrically, yielding the final representation of the pattern for the subsequent CAD modeling. The pattern can be represented as a collection of points (point cloud) or as a line diagram. The illustration shown in Figure 4 corresponds to a line diagram. The point cloud data repressed by a line diagram (the last patter in Figure 4) were first converted into raster graphics to represent the pattern as a grid of pixels using a monotonic color scheme. The raster image was then transformed into a vector graphics format to represent the curves of the patterns for scalability and quality. Finally, a three-dimensional CAD model was generated from the vector image through the operation called extrusion. The rendering results are presented in Figure 5. The CAD model can be used to replicate the pattern using a suitable manufacturing process (e.g., 3D printing or laser cutting).

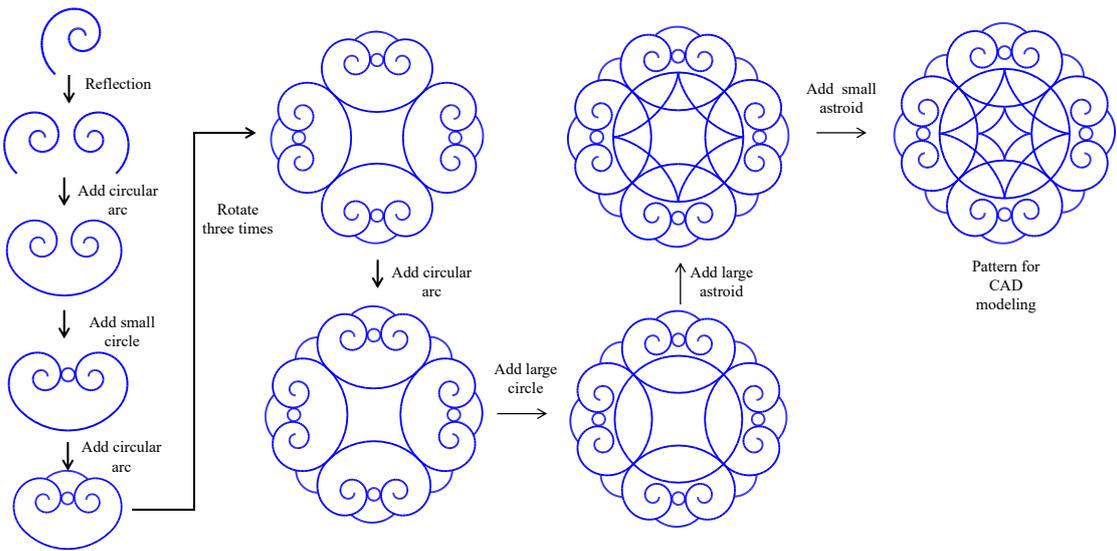


Figure 4. The point cloud model of the pattern.

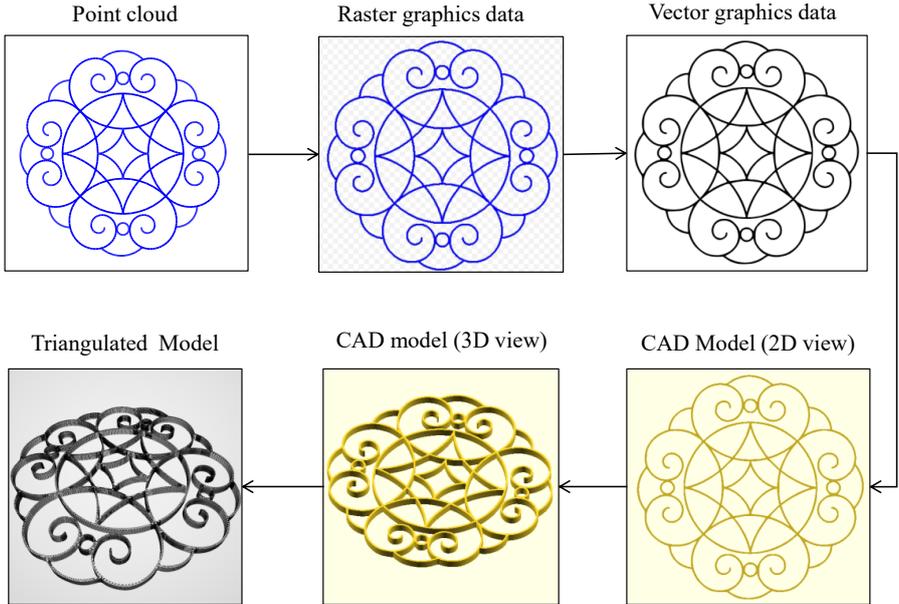


Figure 5. CAD modeling of the pattern.

## 4 CONCLUDING REMARKS

The proposed digitization method can successfully model and digitize the targeted pattern found in a Mongolian artifact. The method can be applied other artifacts in the similar manner. The method exhibits less computation burden for the users. Thus, it can be implemented using limited computational resources, which is perhaps a desirable outcomes as far as cultural artifact preservation is concerns.

However, in this study we considered the motifs that can be represented by algebraic equations (circle, astroid, spiral, and circular arc). There are other motifs (e.g., S-3, A-2, and alike) that cannot be represented in the same way. In this case, an alternative approach would be necessary. In the second phase of this study delves into this issue. The other issue is manufacturability of the CAD models. Additive manufacturing and laser cutting can be used to produce the physical objects based on the CAD model. This issue is also open for further research.

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